Spotlight Flooding: Enabling Point-to-Point Control Connection in Urban UAV Networks

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***Abstract*—The use of Unmanned Aerial Vehicles (UAVs) has been proposed for numerous applications from recreational photography to commercial deliveries and infrastructure monitoring. But their effective deployment depends on the establishment of an Unmanned Aerial Traffic Management (UTM) which in turn requires reliable communication protocols to ensure safe and efficient operations. Recently, Rate Decay Flooding (RDF) was proposed as a novel protocol to enable position sharing among UAVs, realizing one of the major UTM applications. Another application is the provisioning of a redundant control connection which allows for point-to-point communication between a UAV and its operator in case their proprietary primary connection breaks. Every protocol used for this must harmonize well with RDF so that both applications can be realized at the same time. In this work we propose Spotlight Flooding (SLF) and its enhanced version SLF+, which build on top of RDF to realize a fast and reliable point-to-point connection between any two nodes in the network. These protocols are evaluated in an open-source simulator considering two scenarios. First, we consider a single UAV in distress using SLF/SLF+ to explore the performance of our novel protocols for networks of up to 525 UAVs. The results show, that even for large networks, SLF+ achieves a Packet Delivery Ratio (PDR) above 90 % at an end-to-end delay of less than 60 ms. Additionally, we evaluate a scenario of 300 UAVs with an increasing share of UAVs using SLF/SLF+. Again, even if half of the UAVs in the scenario use SLF/SLF+ a PDR above 90 % is achieved at a delay of 142 ms.**

***Index Terms*—UAV Traffic Management, Ad-hoc Routing, NR-V2X, 802.11p, Control Connection**

I. Introduction

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, are aircraft operated without a human pilot aboard. These flying machines can be remotely controlled by human operators or autonomously programmed to execute predefined missions. UAVs come in various shapes and sizes, ranging from small quadcopters used for recreational purposes to large fixed-wing drones employed for long-range surveillance and cargo delivery.

In recent years, UAVs have obtained significant attention and are prepared to play a transformative role in numerous industries and applications. If UAVs are deployed for various tasks, especially in urban or densely populated areas, the effective management of UAV traffic becomes crucial, specially in the urban environment. Without proper coordination and communication, the widespread use of UAVs could pose risks to airspace safety, privacy concerns, and operational inefficiencies.

Consider a scenario where UAVs are employed for tasks such as aerial photography, surveillance, and package delivery in a bustling city environment. The airspace is congested with multiple UAVs operating simultaneously, each with its own mission objectives and flight paths. One of the main use cases of communications among UAVs is the coordination and guidance of vehicles, which is referred to as Unmanned Aerial Traffic Management (UTM) [1]. From a communications perspective, there are two main UTM services [2].

1) Situational Overview: It's crucial to provide up-to-date information on vehicle identities, positions, and intentions. This helps authorities manage air traffic and allows vehicles to avoid collisions. The information is shared so all UAVs and ground entities have a clear view of the current situation, similar to Automatic Dependent Surveillance Broadcast (ADS-B) or Flight Alarm (FLARM), supporting U-Space traffic and identification services [3]. For effective Communication Aided Detect and Avoid (CADA) implementation, UAVs must promptly share their positions to avoid collisions. An ad-hoc network is considered efficient to enable this service. A novel protocol, Rate Decay Flooding (RDF) [4], reduces redundant packets and meets the functional requirement of this.

In RDF, UAVs regularly broadcast position reports across the network, lowering traffic density by reducing data rates at each hop. It can handle position sharing in networks more than twice the size of current flooding protocols and has been proven to work in networks with up to 525 UAVs, enabling a situational overview in a decentralized manner.

2) Control Connection: Another UTM service is to provide a backup control link between the operator and the UAV in case the primary connection (e.g., cellular connection 5G/6G) fails. This is crucial for continuous operation such as rerouting of the affected UAV. In such cases, an ad-hoc network, realized via NR-V2X or IEEE 802.11p/802.11bd [5] can serve as an effective alternative backup solution to be accessible by responsible authority without relying on the proprietary cellular connection. Low latency is a key requirement for this service to enable a direct communication between the

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affected UAV and the ground station/the operator. While RDF is suitable for position sharing, its increased delay in dense U-Space makes it ineffective for direct communication.

The main contribution of this paper is the introduction of an extension to RDF, designed to establish the point-to-point control connection. While RDF manages position sharing, the proposed protocol, Spotlight Flooding (SLF) is designed to reduce the latency when realizing the direct point-to-point communication. This is crucial for authorities to maintain control in emergency situations, ensuring a reliable connection independent of existing infrastructure. Additionally, our evaluation emphasizes dense U-Space environments, where robust UTM services are essential. Following the predictions in [6], we evaluated two scenarios: In the first scenario, we validate the performance of SLF when a single UAV loses its primary connection in networks of up to 525 UAVs. The second scenario examines the impact on realizing the control connection under various fractions of UAV failures in a network of 300 UAVs controlled by three ground stations.

Section II reviews existing infrastructure-less approaches used to realize direct communication in UAV networks. The next section explains the proposed SLF protocol and its enhanced version. Section IV discusses the results, evaluated using Key Performance Indicators (KPIs) of Packet Delivery Ratio (PDR), delay, and control overhead.

II. Related Work

Various ad hoc based routing protocols have been developed for UAV networks, widely known as Flying Adhoc Networkss (FANETs) and broadly categorized into topology-based protocols and geographic routing protocols. This section reviews the existing literature on these protocols, focusing on their systematic methods, advantages, and limitations in the context of large urban UAV networks. We only consider previous work on enabling point-to-point communication, not the position flooding protocols [4], [7]–[9].

A. Topology-Based Protocols

The authors of [10] survey topology-based hop-by-hop protocols in the context of UAV communication, which determine the optimal routing path from source to destination using network topology and link-state information before transmission. These protocols fall into three categories: proactive (M-OLSR, Cartography Enhanced OLSR (CE-OLSR), Directional OLSR (D-OLSR), DSDV), reactive (DSR, AODV, Reactive Greedy Reactive (RGR), and Modified-RGR), and hybrid (ZRP, Temporally-Ordered Routing Algorithm (TORA), Hybrid Wireless Mesh Protocols (HWMP), and SHARP). Most protocols are only evaluated on small networks with no background traffic. A significant challenge for these protocols in large urban UAV networks is to coexist with position sharing that is a requirement for UTM. Proactive protocols enable the selection of the best route but results in high overhead and scalability issues due to constant updates, while reactive protocols introduce higher end-to-end delays due to the time taken for path discovery. Especially rapid and unpredictable changes in topology and link quality can cause pre-selected paths to become outdated, requiring a large amount of control traffic to keep routes up to date.

B. Geographic Routing Protocols

Geographic routing is a prominent method used in UAV networks, where routing decisions are based on the geographical positions of nodes. One of the key advantages of geographic routing is its efficiency and resilience in handling the high mobility of UAVs in FANETs compared to traditional topology-based routing protocols. This approach reduces routing overhead by eliminating the need for route discovery and maintenance processes, which can be challenging in highly dynamic UAV environments.

A core strategy in geographic routing is greedy forwarding, where a packet is forwarded to neighbors closer to the destination, iteratively shortening the path and reducing latency. Despite its benefits, geographic routing faces challenges like the local minimum problem, where packets get stuck at nodes with no closer neighbors, and network voids, where gaps in UAV coverage disrupt routing, potentially causing packet loss or delays.

Greedy Perimeter Stateless Routing (GPSR) [11] utilizes greedy forwarding, where nodes attempt to forward packets to the neighbor closest to the destination in terms of geographical distance. If greedy forwarding fails, the protocol switches to perimeter forwarding, navigating around network voids using the right-hand rule. In GPSR the sender of a packet decides the next hop. In scenarios with high packet loss, this requires a retransmission mechanism incurring additional delays.

Variants of GPSR are proposed which add additional metrics to the selection of the next hop. E.g. Geographic Load Share Routing (GLSR) [12] the current queue state of neighboring nodes is taken into consideration. Utility Function-based Greedy Perimeter Stateless Routing (UF-GPSR) [13] introduces more parameters like residual energy ratio, distance degree, movement direction, link risk degree, and speed. In our approach, we take inspiration from GPSR also applying a greedy forwarding mechanism. Nevertheless, we tightly integrate our approach with RDF as explained in the following section.

III. Protocol Description

The extension of the RDF protocol to achieve direct point-to-point communication is detailed here.

A. Rate Decay Flooding (RDF)

RDF is a protocol for facilitating position sharing in large urban UAV networks. The core idea here is to prioritize data from nearby UAVs compared to UAVs at a larger distance.

The process is depicted in Figure 1. Node 1 emits its position update. Now all receivers calculate the same RDF delay (red bar). In addition, each node calculates a contention delay, inversely proportional to the distance from the sender (green bar) as proposed in [14] and set a timer until these

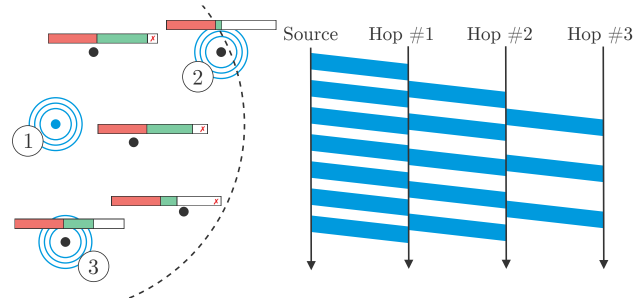

Figure 1: Schematic of the forwarding process used in RDF

delays expire. As Node 2 calculates the shortest delay, it forwards the packet first. All its neighbors that overhear Node 2 forwarding now cancel their timers to avoid redundant forwarding of the packet. Only Node 3, that is too far away from Node 2, also forwards the packet once its timer expires. This procedure causes a behavior as shown on the right side of Figure 1 effectively *thinning out* the message sequence chart the further a packet is forwarded into the network. Our previous results have proven the stability of RDF up to 525 UAVs when sharing the position updates.

B. Spotlight Flooding (SLF)

With position sharing, packets from every source are eventually received by every other node. SLF utilizes this logical connection to establish point-to-point communication between any two nodes (e.g. an Operator and its UAV). This is achieved by adding a destination header field to a RDF packet and piggybacking any additional information on top of the RDF packet (e.g. a steering command for the UAV). While this alone already establishes communication between two nodes, the rate decay mechanism causes very large delays after only a few hops. Therefore, SLF aims to accelerate packets toward their destination by taking inspiration from Greedy Forwarding.

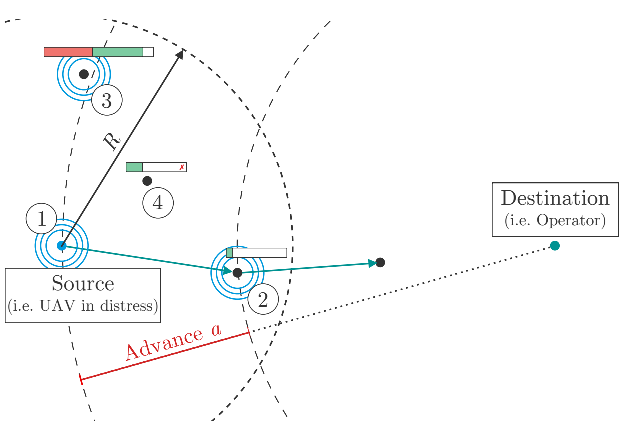

Figure 2: Schematic of the forwarding process used in SLF

The behavior of SLF is depicted in Figure 2: Node 1 (a UAV in distress) acts as the source and wants to send information to a destination (its operator). In doing so, it adds the destination ID to an emitted position update and appends an additional information block to the packet intended for the destination. This packet is now received by all neighbors of Node 1. As the packet contains the position of the sender, and they have learned about the position of the destination through position sharing, they can now calculate the advance a towards the destination. If a receiving node has a negative advance, it executes RDF as described above (Node 3). Otherwise, if they calculate a positive advance a towards the destination, they skip the delay imposed by RDF and only calculate a timer inversely proportional to their advance (Node 2) and forward the packet afterwards. Again, if a node overhears the forwarding of the packet before their delay has passed, they forgo their own forwarding (Node 4). Once Node 2 forwards the packet, the process repeats. Different from ordinary Greedy Forwarding protocols, SLF does not need a backup mechanism. Even if Node 2 turns out to be a dead end, the packet is still forwarded by Node 3. Although additional RDF delays are incurred whenever a dead end is encountered, RDF's forwarding mechanism will eventually circumnavigate any void. At this point potential forwarder will again calculate positive advances and accelerate the packet towards the destination. In our scenario, the point-to-point application generates a packet every second. The position sharing application emits one packet every 120 ms. To combat the ample packet loss caused by the position sharing in our scenario, we send copies of the same Point-to-Point packet with every position update resulting on average in each packet being sent 8 times from the source.

C. Advanced Spotlight Flooding (SLF+)

To improve the reliability of the protocol, and reduce the delays further, we introduced an immediate forwarding area in our improved protocol version, SLF+, as shown in Figure 3. Again, receiving nodes with a negative advance (Node 3) follow RDF. Further, we introduce a threshold a_{thr}. If a node calculates an advance larger than that (gray area), it forwards the packet immediately, only adding a small jitter. While this aims to reduce the delay it also has the side-effect of generating redundant packets if more than one node is inside the immediate forwarding area (Nodes 2a and 2b). Of course, the threshold must be selected carefully. If set too high, the probability that any node is inside the immediate forwarding area, becomes low and therefore defeats the purpose of the immediate forwarding altogether. On the other hand, if set too low, there will be many nodes that forward immediately resulting in excessive traffic on the network.

To solve this issue, we apply a mathematical estimation of the number of nodes inside the immediate forwarding area. For this we model the position of the nodes as a two dimensional Poisson process with a constant density of $\rho = 12\,\mathrm{UAVs/km}^2$. This allows us to calculate the probability of having a certain number of nodes k in a immediate forwarding area of size A_{fwd} as

$$\Pr(K = k) = \frac{(\rho A_{\mathrm{fwd}})^k}{k!} e^{-\rho A_{\mathrm{fwd}}} \tag{1}$$

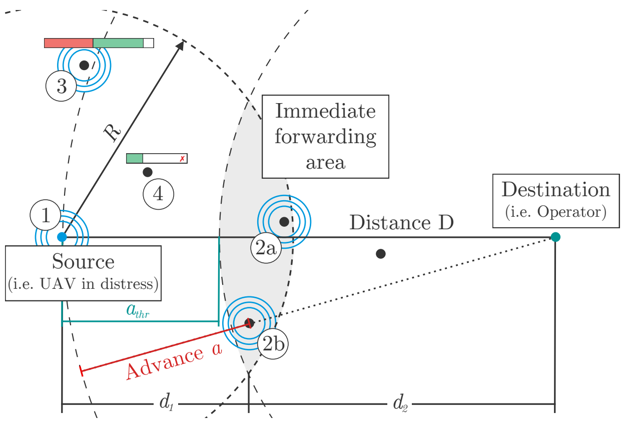

Figure 3: Schematic of the forwarding process in SLF+

Assuming a nominal communication range $R = 509\,\mathrm{m}$ (obtained through simulation of 802.11p) and a distance to the destination $D = 10\,\mathrm{km} \gg R$, we can calculate the area of the immediate forwarding area as

$$\begin{aligned} A_{\mathrm{fwd}} = R^2 \cdot \arccos\left(\frac{d_1}{R}\right) \\ - d_1\sqrt{R^2 - d_1^2} \\ + (D - a_{\mathrm{thr}})^2 \cdot \arccos\left(\frac{d_2}{D - a_{\mathrm{thr}}}\right) \\ - d_2\sqrt{(D - a_{\mathrm{thr}})^2 - d_2^2} \end{aligned} \tag{2}$$

with

$$d_1 = \frac{R^2 - (D - a_{\mathrm{thr}})^2 + D^2}{2D}, \quad d_2 = D - d_1 \tag{3}$$

The probably to have at least one node in the immediate forwarding area and the probability to have at least two nodes is shown in Figure 4. Based on this, we have selected a value of $a_{\mathrm{thr}} = 150\,\mathrm{m}$ yielding a probability of having at least one immediate forwarder of more than 95 % and a probability of having at least two immediate forwarder of roughly 80 %. While this is a rather aggressive setting our estimation allows for the analytical selection of other thresholds or even an adaptive selection of the threshold as long as a local estimate of the node density is known.

IV. Results

We evaluate the both SLF and SLF+ in a ns-3 based simulator first introduced in [4]. The implementation of SLF and SLF+ was made publicly available in [15]. As a link-layer we selected IEEE 802.11p [16], which is a promising technology for large scale urban UAV networks [2]. All simulations were repeated 100 times, where possible 95 % confidence intervals are shown. In our scenario, we consider a square shaped simulation area sized so that a constant density of $12\,\mathrm{UAVs/km^2}$ is preserved. The density was selected based on a parcel delivery use case proposed in [6] and

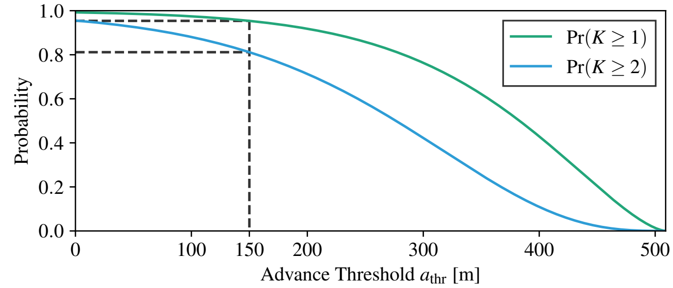

Figure 4: Probability to have at least one and two nodes in the immediate forwarding area for various values of a_{thr}

is in line with predictions for the UAV density for major German cities [2]. Since real world mobility of large-scale urban UAV networks is not available, we consider random direction mobility with velocities ranging from 22 m/s to 33 m/s.

A. *Scenario 1:* A Single UAV in Distress

In the first scenario, we consider a scenario as depicted in the lower right of Figure 5, where a variable number of UAVs move through the airspace. A ground station is located at the center of the simulation area. In each simulation we randomly pick one UAV as a UAV in distress which uses SLF to initiate a redundant control connection with the ground station. The position of the UAV in distress is uniformly random selected within the simulation area. All other UAVs perform position sharing using RDF.

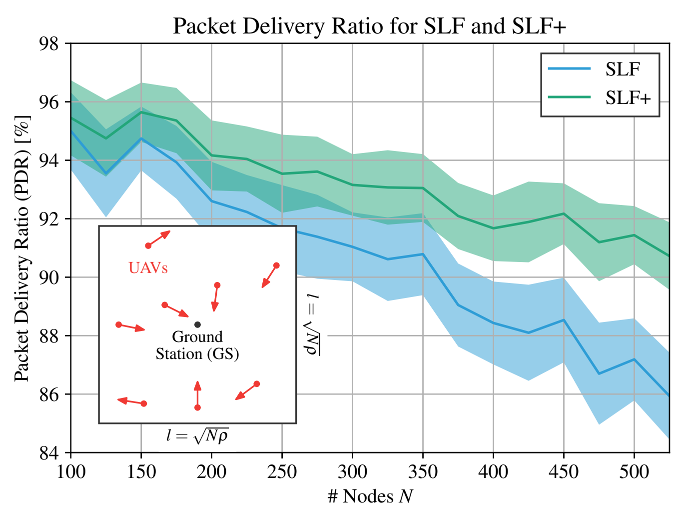

Figure 5: PDR for network sizes from $N = 100$ to 525 for SLF and SLF+

Figure 5 shows the PDR of the point-to-point connection as the number of unique received packets divided by the number of unique sent packets. We can see that the initially both SLF and SLF+ achieve roughly the same PDR. For larger networks though, the PDR of SLF drops to 86 %, while the PDR for SLF+ remains above 90 % for all network sizes. We also observe a high variance in PDR between simulation runs as indicated by the large confidence intervals. This is a result of the random selection of the position of the UAV in distress as a higher PDR is achieved if the UAV is only a few hops away from the ground station.

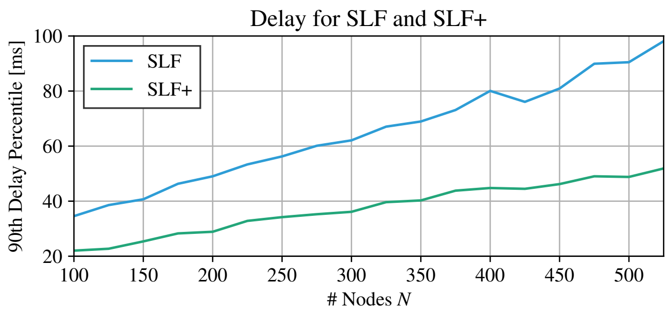

Figure 6: 90th percentile of the end-to-end delay for network sizes from $N = 100$ to 525 for SLF and SLF+

Additionally, we measured the end-to-end delay of the control packets. The 90th percentile of the delay over all simulations is shown in Figure 6. For SLF, the delay remains below 40 ms for networks of less than 150 nodes and rises up to 100 ms. For SLF+ we can observe the effect of immediate forwarding: Over all network sizes, the delay is roughly half of that incurred by SLF.

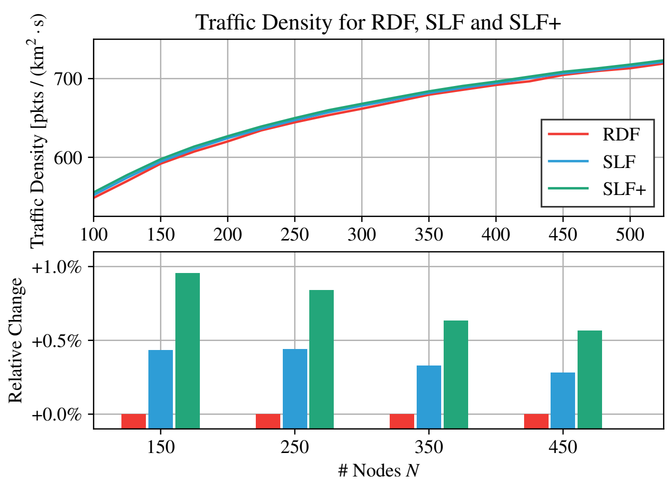

Figure 7: Traffic Density for network sizes from $N = 100$ to 525 for SLF and SLF+

It is always important to quantify the cost of a protocol. This is shown in Figure 7 where we show the traffic density for all network sizes. The traffic density is defined as the number of packets sent divided by the total simulation time and simulation area. It is a measure of how much load the protocol generates. As a baseline this is also measured for RDF without any UAV performing SLF. From the upper part of the Figure we can see that the traffic density rises for larger networks, but there is little difference between the three protocols. This is quantified in the lower part of the figure. Here, we show the relative increase in traffic density compared to RDF. For SLF this value is below 0.5 % for networks with 150 nodes and decreasing for larger networks. As expected higher values are measured for SLF+ as the immediate forwarding causes redundant transmissions. Nevertheless, even for SLF+ the relative increase in traffic density remains less than 1 %.

B. ***Scenario 2:*** *Partial Outage of the Primary Connection*

While scenario 1 confirms the effectiveness of SLF and SLF+ when only a single UAV utilizes the redundant control connection, in this scenario we aim to study the effect of many UAVs using SLF at the same time.

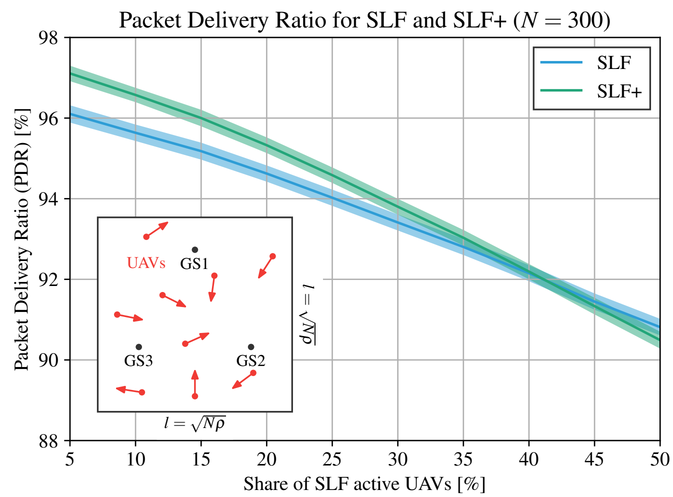

Figure 8: PDR for a network of $N = 300$ nodes and varying share of SLF active UAVs using SLF or SLF+

For this purpose we devised a scenario as shown in the lower right of Figure 8. We consider a fixed network size of $N = 300$ nodes all of these nodes perform position sharing using RDF. The scenario has 3 ground station signifying 3 different drone operators in the region. A variable share of UAVs ranging from 5 % (=15 UAVs) to 50 % (=150 UAVs) has lost their primary connection and uses SLF to communicate with a ground station. Each UAV is randomly assigned to one of the ground station. The measured PDR is also shown in Figure 8. While the PDR for both SLF and SLF+ decreases with a larger share of UAVs using SLF, both protocols consistently achieve PDRs of above 90 %. For 5 % of SLF active UAVs SLF+ has an advantage of around 1 % in PDR. With larger shares, this advantage diminishes up to a share of 40 % where SLF shows a higher PDR. This indicates that a less aggressive configuration of the immediate forwarding area would be beneficial at this point.

The 90th percentile of the end-to-end is shown in Figure 9. For both protocol variants the delay increases. It is notable that the increase in delay has a non-linear behavior. While changing the share of SLF active UAVs from 5 % to 10 % of from 45 % to 50 % has little effect, the increase in the mid-ranges causes the delay to increase steeply. As in scenario 1, we can still observe the advantage of the immediate forwarding area of SLF+.

Finally, the traffic density incurred in scenario 2 is shown in Figure 10. As all simulations have the same number of

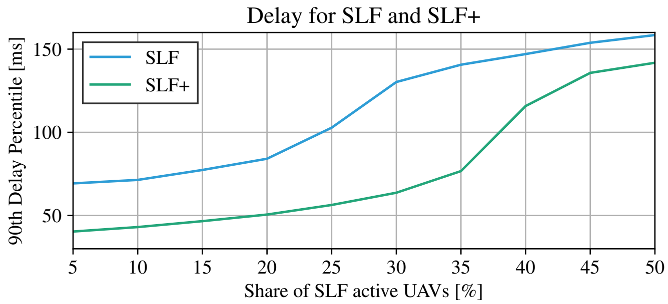

Figure 9: 90th percentile of the end-to-end delay for a network of $N = 300$ nodes and varying share of SLF active UAVs using SLF or SLF+

Figure 10: Traffic density for a network of $N = 300$ nodes and varying share of SLF active UAVs using SLF or SLF+

nodes, the traffic density for RDF remains constant. For SLF and SLF+ we see a significantly higher traffic density. For a share of 40 % of SLF active UAVs the traffic increases by 40 % using SLF and 60 % using SLF+.

V. Conclusion

This paper finalizes our work on proposing a comprehensive solution for distributed UTM services, focusing on situational awareness through position sharing among UAVs and establishing a redundant point-to-point control connection. The previously proposed RDF [4] protocol demonstrated situational awareness scaling up to 525 UAVs in a dense U-Space. In this paper we propose SLF as a protocol to realize a point-to-point control connection and evaluate it under varying fraction of UAVs in distress, which mimic emergency situations like loss of primary connection or re-routing of a malicious UAVs broadcasting falsified GPS positions [17].

Both protocols are complementary, adapting to application needs, and operate without relying on infrastructure, allowing U-Space to function independently of proprietary communication technologies used by different UAV operators. The evaluated scenario parameters are based on a parcel delivery scenario projected for 2035 in cities like Hamburg, Berlin, and Munich with an average density of 12 UAVs/km^2.

As future work, both RDF and SLF protocols are implemented on RPI based platforms and the experimental testing is in progress using NR-V2X technology [5].

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